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PROPULSION INSTRUMENTATION RESEARCH

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As was stated in the overview, "the goal of the Propulsion Instrumentation Research Program is to provide the instrumentation technology advances needed to support future aeroproplsion research and development."

A hallmark of this work is that the sensors and measurement systems being developed are not intended to be used on operational propulsion systems. They are aimed at experiments for engine development, component development, and analytical code validation. Although sensors and/or systems for operational engines sometimes grow out of this work, they are not the goal.

A further characteristic of this work is that it is frequently blind about whether the application is for aero or space propulsion. Some of the following examples are currently being developed for space propulsion systems, but they are also applicable to aeropropulsion.

Propulsion Instrumentation Research

Goal: To develop the sensors and measurement systems required to determine component performance and to validate analytical codes

Drivers:
- Hostile environments
- New materials (primarily ceramics)
- Need for spatially and temporally resolved data for codes

Approach:
- Contact sensors (minimally intrusive)
- Optical measurement systems (nonintrusive)

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Propulsion Instrumentation Research is driven by the need to determine component performance and to validate analytical codes.

The goal of much current aeropropulsion work is to increase performance. This is leading to higher temperatures and generally more hostile environments, which in turn, is leading to the use of new materials such as ceramics.

The cost of cut and try development has become prohibitive, so design data obtained via codes and via component testing must be as detailed and as credible as possible. Code validation requires that data be obtained with very high spatial and temporal resolution; in addition, it must be obtained in a nonintrusive manner since its accuracy and applicability could be compromised by the presence of a sensor that perturbs the very measurement being made.

Our response to these problems has been to work on contact sensors and optical measurement systems. The contact sensors are usually thin sputter-deposited films for thermocouple, strain gages, and heat flux gages. The optical systems usually feature a laser beam, or beams, and complex methods of data collection and processing.

Propulsion Instrumentation Research

- Contact Sensors
  - Plug-type and thin-film heat flux gages
  - Thin-film thermocouples on ceramics
  - Surface strain gages

- Remote Optical Measurement Systems
  - Speckle interferometry for remote strain
  - Multipoint/multiparameter (NASP)
  - PC-based particle imaging velocimetry
  - Rayleigh scattering diagnostics

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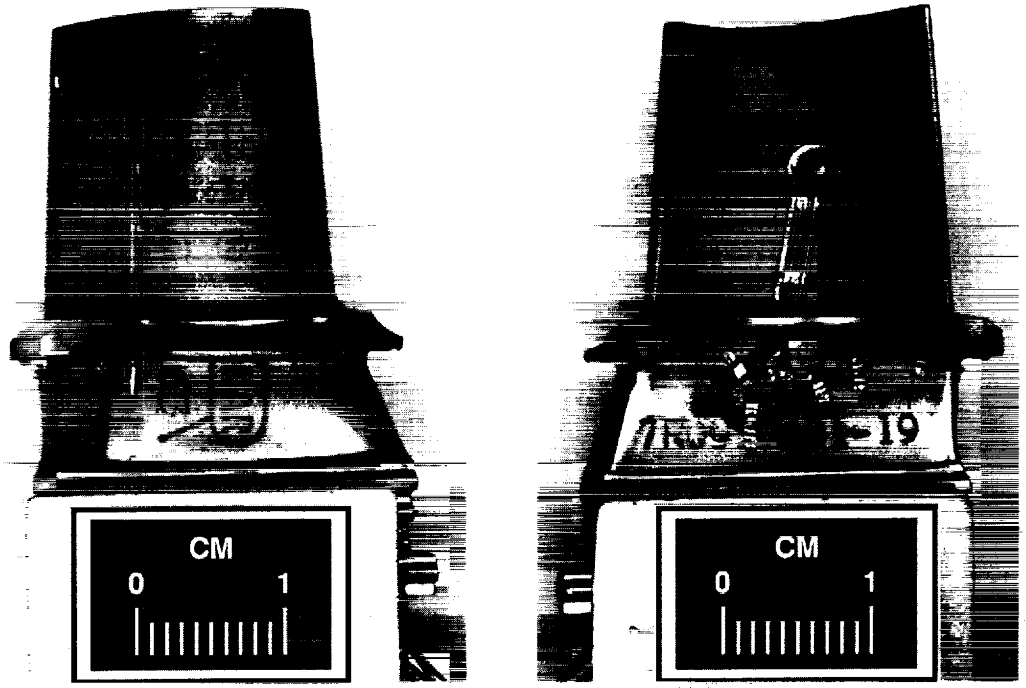
This report will cover a sampling of both the minimally intrusive contact sensors and the nonintrusive optical measurement systems. This is not a complete listing of the work we are doing, but it is a representative sampling of the most recent and pertinent work.

Plug-Type Heat Flux Gage



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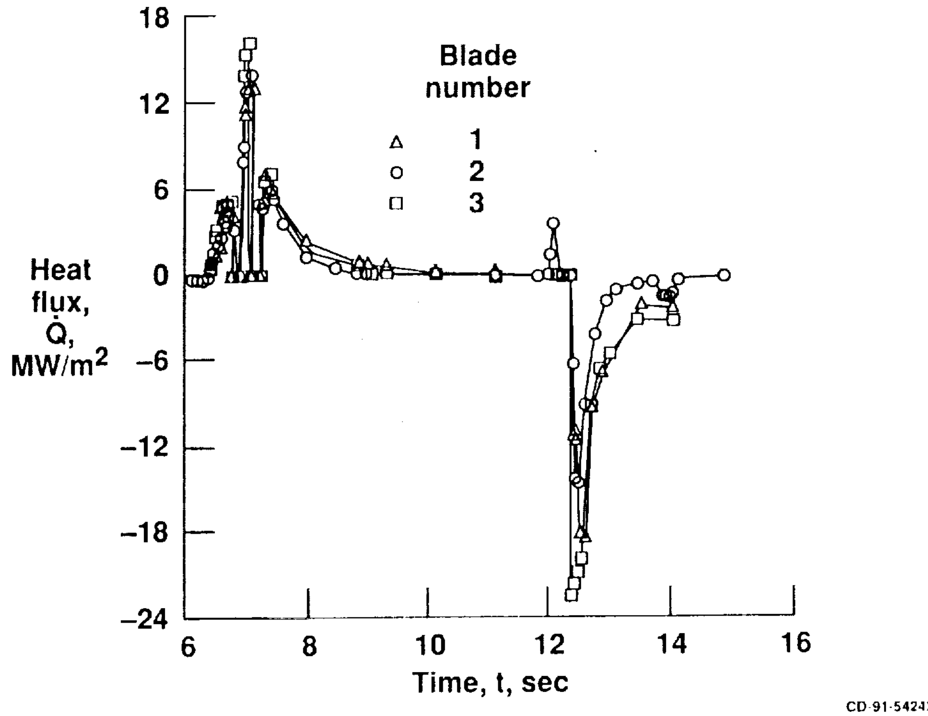
The first topic is heat flux gages. Our goal is to develop sensors to measure the heat flux on surfaces in the hot section, such as on blades or vanes.

The heat flux sensor pictured here is called a plug-type sensor. It is electron-discharge-machined right into the blade or vane and is therefore somewhat more intrusive to the blade than would be a thin-film sensor; however, it still doesn't disturb the gas flow.

This heat flux sensor is a post that is machined into the blade; the volume surrounding the post and behind it is filled with trapped air which acts as a thermal insulator. Very fine thermocouple pairs are splotted along the length of the post, and the wiring is brought out through small grooves machined into the backside of the blade. An additional thermocouple is buried in a small groove on the front side with the junction centered over the place where the post would be if it were machined all the way through. The post is treated as a one-dimensional heat flow device. The rates of change of the thermocouple signals can be processed to yield the instantaneous heat flux entering the front side of the blade.

The photographs show this gage installed on a space shuttle main engine (SSME) high-pressure fuel turbopump turbine blade. On the left is the front or suction side of the blade. This photograph was taken before a thin foil was welded over the thermocouple leads to smooth the installation. Similarly, the right photograph shows the back or pressure side prior to the closeout for smoothing. The rear of the post is visible in this figure.

Heat Flux Measured in SSME Turbine Blade Tester

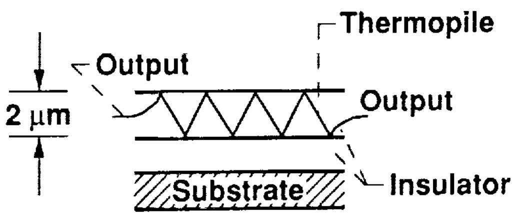


The blade in the previous figure (blade 2 in this graph) and two more just like it were tested in a blade cascade cyclic tester at NASA Marshall Space Flight Center. Each blade contained one of the plug type gages, but their locations varied.

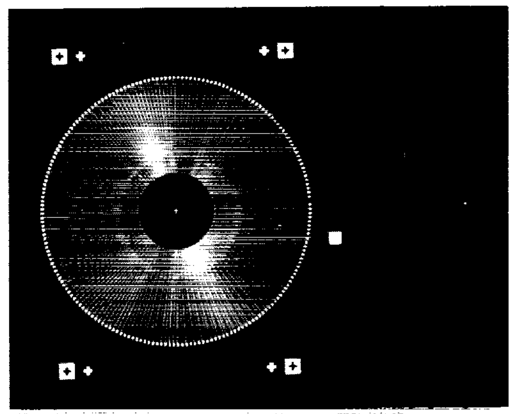
The tester produces thermal transient conditions very similar to those experienced in the startup and shutdown of the SSME. Blade 2 was mounted in the center of the three-blade cascade where the conditions were most like those in the turbine. Previous modeling results had shown that the transient heat flux was very large and potentially damaging to the blades. This had not been experimentally verified until this test.

This graph shows a plot of the heat flux in megawatts per square meter versus time in seconds for each of the three blades. The initial (positive) flux is a result of the cold blade being suddenly exposed to the combusting hydrogen and oxygen. The later (negative) values are a result of the blades being suddenly cooled by the cryogenic purge. Note that these heat flux levels are very large relative to those seen in aero turbines.

Thin-Film Heat Flux Gage



Principle of operation



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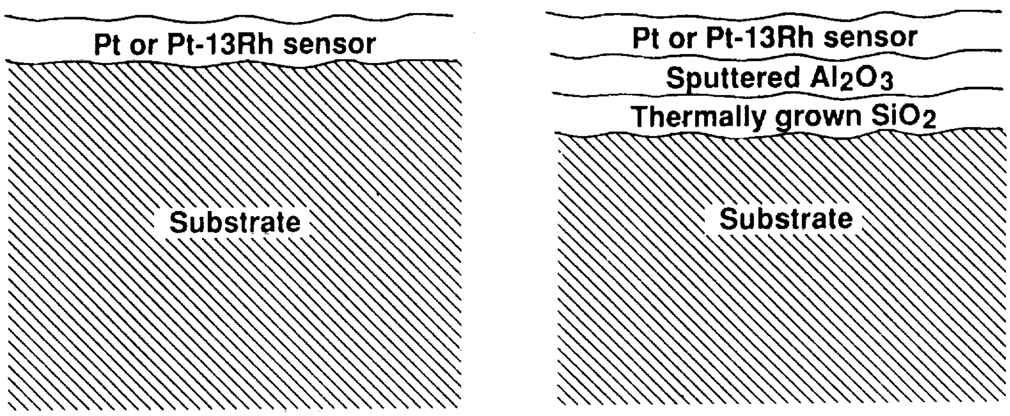
On the left in this figure is a schematic of our latest design of a thin-film heat flux sensor. The photograph on the right shows the most recent version of the design. This sensor is minimally intrusive to both the surface material and the gas stream.

The principle is to measure the temperature drop across a thin film of insulating material of known thermal conductivity. If the film is very thin, though, the temperature difference is so small that a single thermocouple pair cannot produce a signal large enough for reasonable measurement. Our approach is to capitalize on processes developed in the microelectronics industry to put a large number of thermocouple pairs on each side of the film and to connect them in series to form a thermopile. Thus, we obtain a usable signal from a very thin film.

The recent sensor pictured here has 100 thermocouple pairs on each side of a thin thermal barrier material. A few of these sensors have been fabricated, but work continues toward optimization of the many processing steps required. Success with this on flat surfaces will lead to the next step fabrication of this type of device on curved surfaces such as blades or vanes.

Thin-Film Thermocouples on Ceramic Substrates



Electrically insulating ceramic substrates

Si_3N_4
Al_2O_3
Mullite

Electrically conducting ceramic substrates

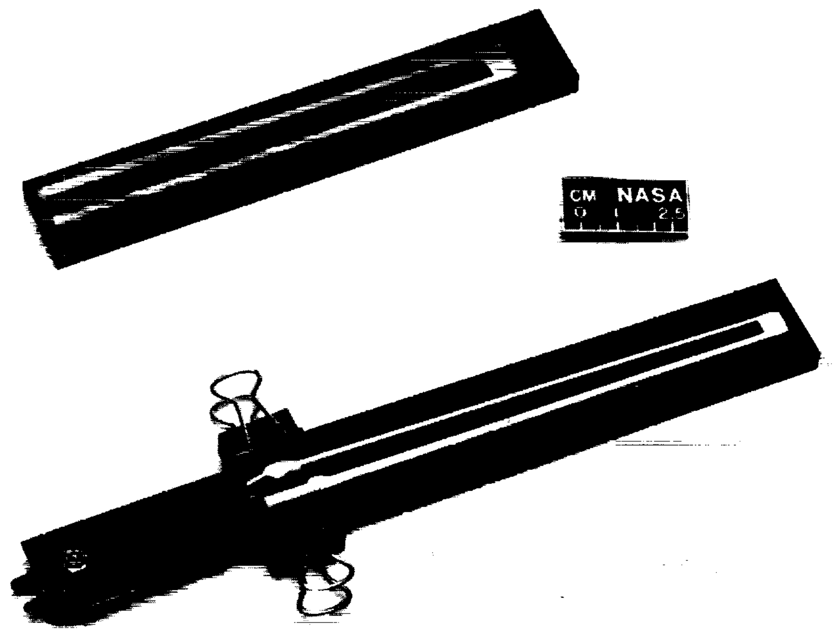
SiC

CD-91-54222

At the last conference, in 1987, we showed the results of our program to develop thin, sputter-deposited thermocouples for metallic turbine blades and vanes. Such thermocouples are currently being applied and used routinely in development facilities.

Our program is now driven by the need to make these surface temperature measurements at higher temperatures which typically means on ceramic materials. This figure illustrates the complexities of applying such sensors to different types of ceramics. Those which are electrically conducting require a carefully applied insulating layer under the thermocouple, as did the metals. Others, which are electrically insulating, do not require this extra step and thus are usually simpler.

Thin-Film Thermocouple on SiC Substrate at Two Stages of Fabrication Process



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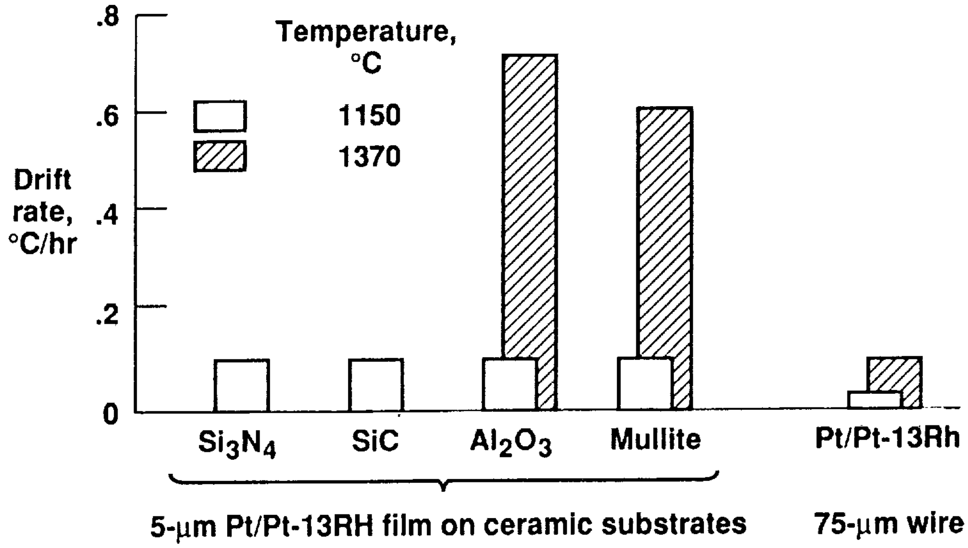
Here we see two thin-film, sputter-deposited Pt/Pt-13Rh thermocouples on SiC substrates. Two stages of the process are shown: the upper photograph shows the thermocouple before the lead wires have been welded to the films and the lower one shows a similar sample after lead wires have been attached.

Drift Rates for Thin-Film Thermocouples



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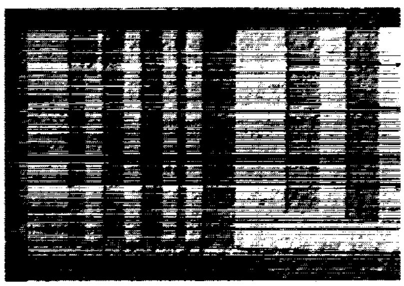
This chart shows the drift rate (in degrees Centigrade per hour) of thin film thermocouples on ceramic substrates held at elevated temperature. Data are shown for four different ceramic substrates at two temperatures. Drift data for comparable bare wire thermocouples are also included for comparison.

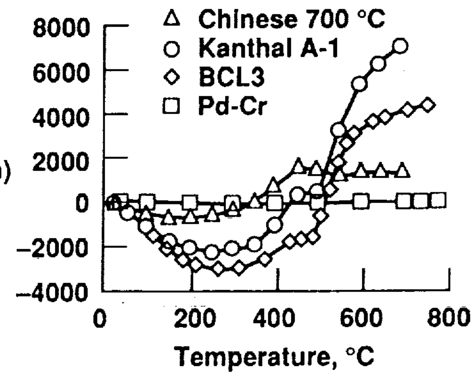
There are no data shown for Si_3N_4 or SiC at the higher temperature, because these materials exhibited an oxidation problem and a structural change, respectively, before reaching this temperature. This behavior makes thermocouples on these materials unusable at elevated temperatures.

Strain Measurement System Development

Miniature Resistance Strain Gage



Compensated Pd-Cr based wire strain gage



Apparent strain vs. Temperature
Pd-Cr gage factor, 1.3; others, 2.0

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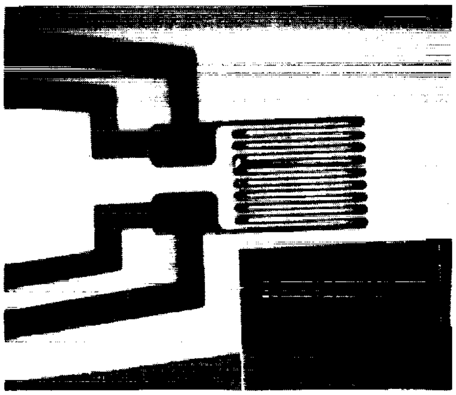
We are working on several approaches to measuring surface strain at high temperatures. The first extends the use of wire gages to elevated temperatures by carefully selecting the alloy. The second uses this same alloy in the form of a thin-film strain gages. The third approach uses a remote optical technique which will be discussed shortly.

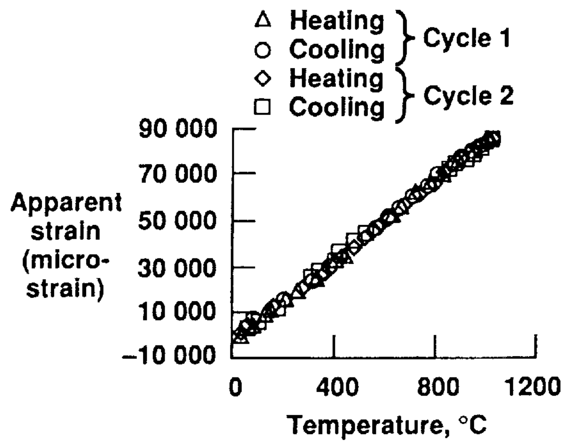
This figure shows wire gage made of a new alloy, Pd-Cr. Is temperature-compensated by use of a section of Pt resistance wire.

On the right, the residual apparent strain of this temperature-compensated Pd-Cr gage is compared with those of the best compensated gages previously available or reported. All of the latter gages are variations of the alloy Fe-Cr-Al. The much smaller residual apparent strain of the Pd-Cr gage demonstrates that compensation of this type of gage is far more successful than compensation of the Fe-Cr-Al gages.

Pd-Cr Based High-Temperature Static Strain Gage



Uncompensated Pd-Cr
thin-film gage



Apparent strain vs. Temperature
Gage tested after thermal cycle to
1050 °C; gage factor = 1.8

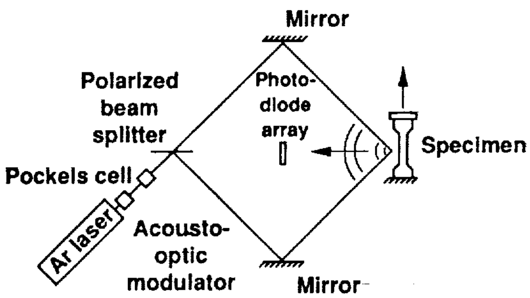
CD-91-54227

This figure shows the Pd-Cr alloy fabricated into a sputtered thin-film gage. This gage has not yet been temperature compensated as was the wire gage shown previously. We are currently working on the compensation.

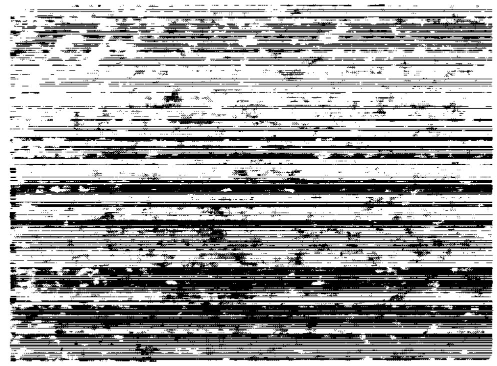
The plot on the right shows that the apparent strain versus temperature of this uncomensated gage is very repeatable over a wide temperature range and through multiple heating and cooling cycles. Repeatability of this nature is crucial if the gage is to be useable.

In addition, the plot is also very linear, which is a necessity for achieving minimal residual apparent strain after temperature compensation.

Speckle Interferometry for Remote Strain Measurements



Laser speckle strain measurement system



Speckle pattern

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The remainder of this section will deal with the remote optical measurement systems.

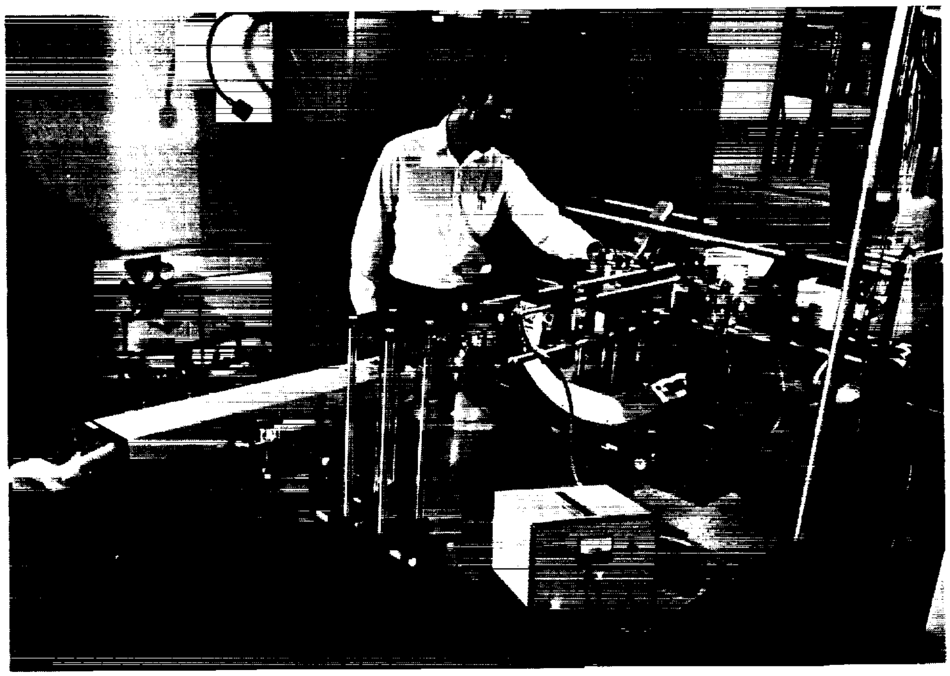
Here is shown an optical technique for remotely measuring strain. It is aimed at those situations where the temperature is beyond the gage alloys and/or where the surface strain is large enough to enter the plastic region.

The technique depends on the fact that the speckle pattern produced by impingement of laser light on a surface is caused by slight irregularities in the surface. This speckle pattern thus moves when the surface is strained. Electronic photographs of this pattern are taken before and after straining, and are then processed to track the speckles; thereby measuring the strain.

The left illustration shows the system schematically. The speckle pattern (example on right) is photographed before and after strain from two different directions. Processing of all four images allows the strain to be separated from any rigid body motion which might have occurred along with the strain.

A majora concern in this system is the large amount of processing required. Efforts are underway to reduce the processing time required.

Laser Speckle Strain Measurement System



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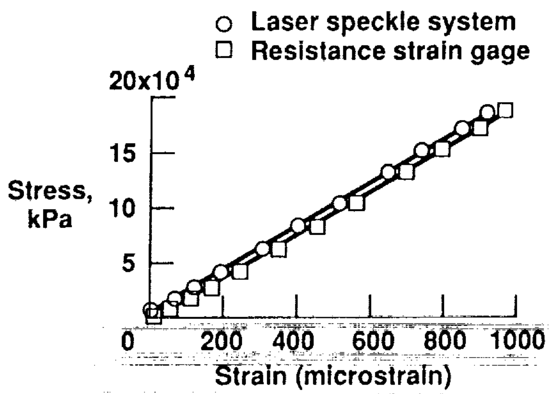
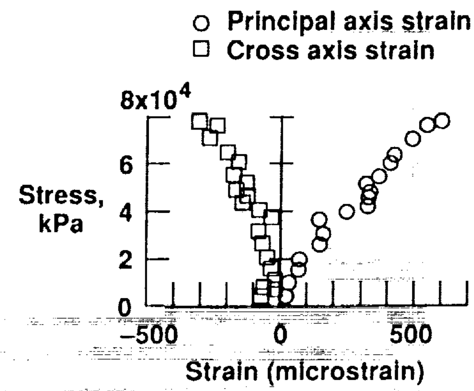
This is a photograph of the laser speckle strain-measuring system in the laboratory. The tensile testing machine is on the right. This system was initially developed by using one-dimensional photodiode array, which simplified the processing relative to that required for a two-dimensional charge-coupled device (CCD) camera array. The center of this photograph shows the goniometer stage which allows the axis of the measurement to be varied so that two-dimensional maps can be generated.

Current work is concentrating on using a two-dimensional CCD camera and the attendant complexity of trying to process the strain map more rapidly. A second system is being developed for fiber applications.

Laser Speckle Strain Measurement System



Room temperature comparison with resistance strain gage



Measurement at 700 °C

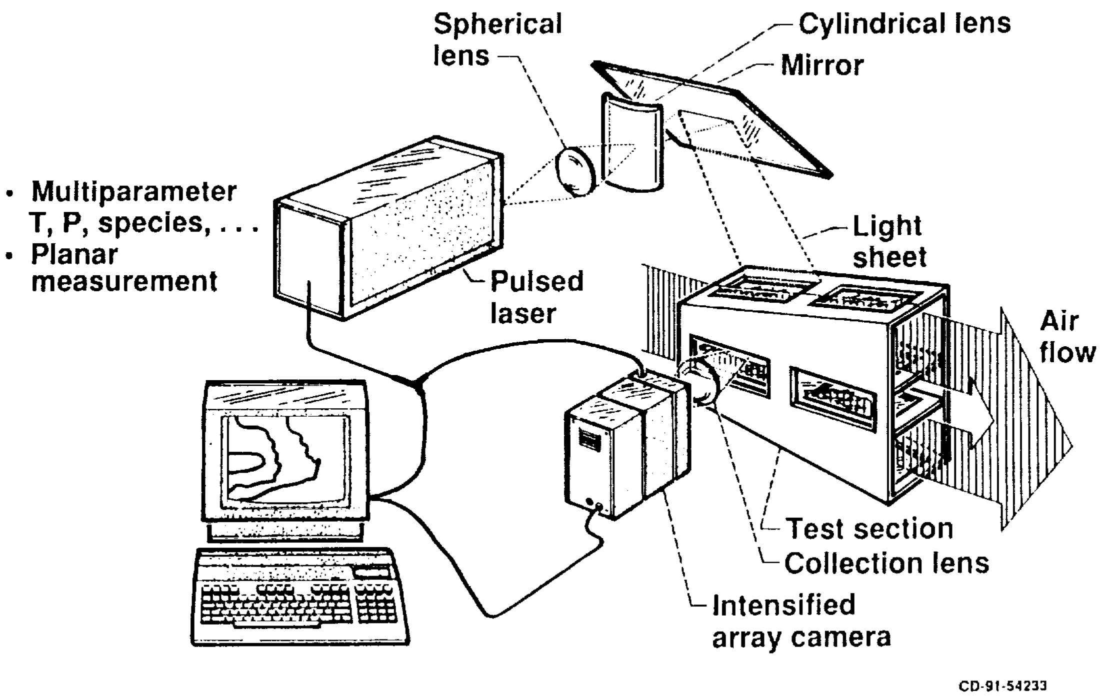
CD-91-54231

The plot on the left side of this figure shows a comparison of the strain measured by the speckle system with that measured by a conventional strain gage. These data were taken at room temperature so that the conventional strain gage could operate accurately. Agreement is excellent except for a small constant offset.

The other side of this figure shows data taken on a specimen held at 700 °C. The right half of this plot shows principal axis strain versus stress, and the left half shows cross axis strain versus stress. The slope of the principal axis data is in agreement with the elastic modulus for this material, and the slope of the cross axis data agrees well with Poisson's ratio.

Work is currently progressing toward testing specimens at higher temperatures.

Hypersonic Flow Diagnostic System

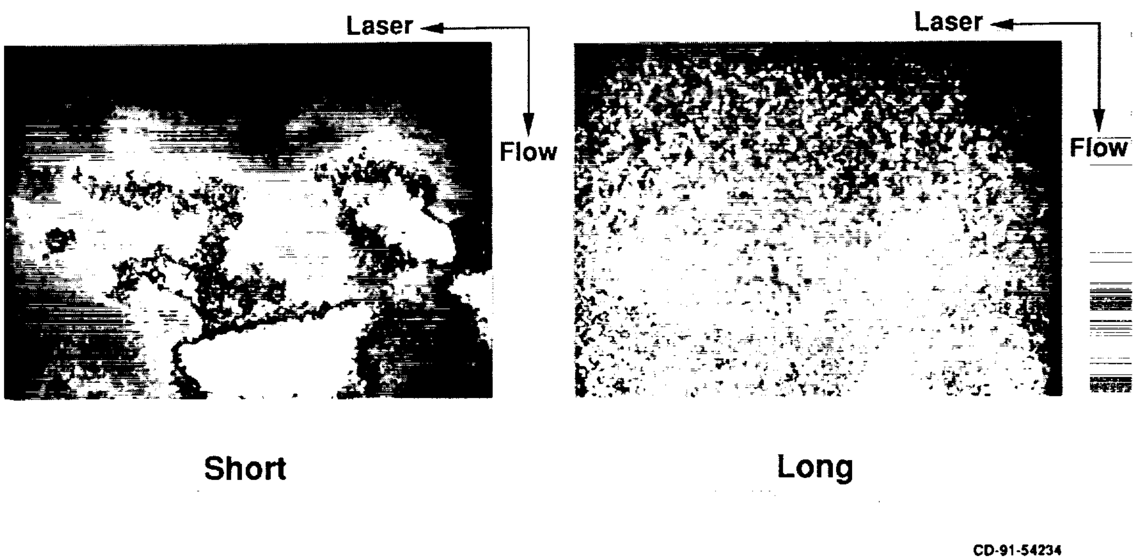


This is the Hypersonic Flow Diagnostic system currently being developed for NASP propulsion system research. The basic idea here is to illuminate a whole plane of the scramjet gas path with laser light and to use the resulting fluorescent emissions, spatially and spectrally resolved, to obtain a planar measurement of multiple variables. This includes such measurements as the concentrations of various species resulting from the combustion process and also the temperature of the gas.

The system is being extended by the use of two lasers and two cameras. This will allow two species to be measured simultaneously or temperature to be measured, by means of two spectral lines. Some major species, such as water, cannot be detected with this technique of laser-induced fluorescence. A Raman scattering based subsystem is being added to measure these species. However, Raman scattering is too weak to be reliably detected when the beam is spread into a sheet, so these will be point, not planar, measurements.

We plan to extend this to velocity measurement also.

Planar Laser-Induced Flourescence Measurements of OH Concentration in a Scramjet Combustor



Shown here are the results of using a prototype of this system on the exhaust of a scramjet combustor. These represent the OH concentration for a short combustor configuration (left) and for a longer one (right). The more uniform mixing achieved with the longer combustor is evident in this picture.

Similar maps have been achieved for other species concentrations as well as for temperature distribution. Quantitative as well as qualitative data will bae obtained from this system.

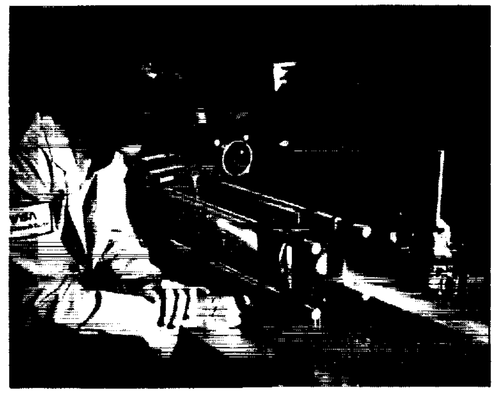
Particle Imaging Velocimetry

Lewis Developed Vector Scanning Technique

Provides 2-dimensional map of velocity magnitude and unambiguous direction

Features

- **Provides fast accurate data reduction without specialized processing hardware (hours of processing time reduced to a few minutes on a PC)**
- **All-video system for electronic processing**
- **Compatible with low number-density seeding**
- **Won R&D 100 award for 1989**



Particle imaging velocimeter

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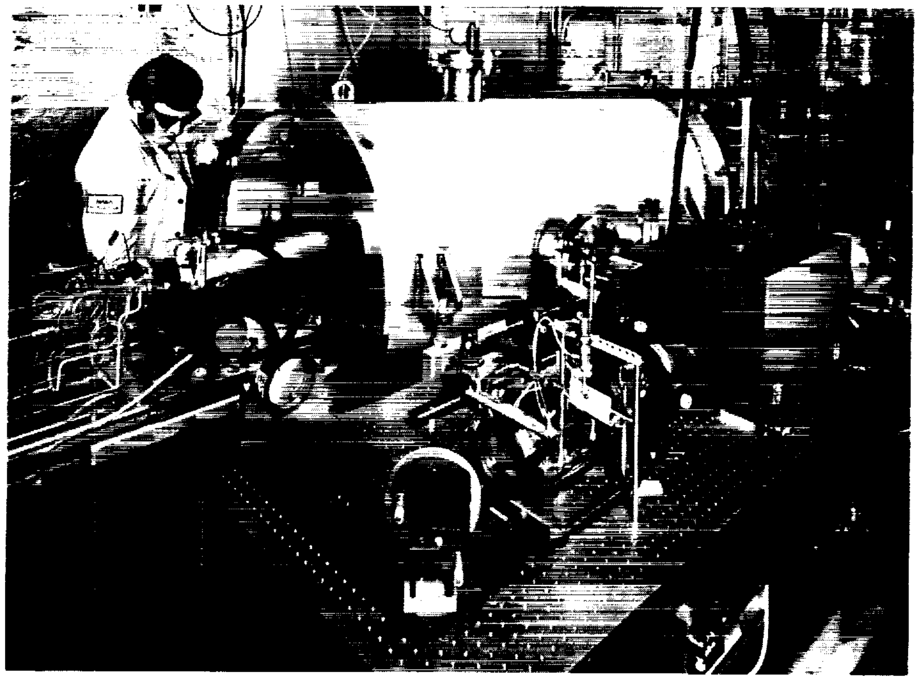
The particle imaging velocimeter, shown on the right in this figure, is a method of mapping the flow velocity in the gas path. By repeatedly photographing (electronically) an entrained seed particle distribution as it progresses in time, one can identify the tracks of individual particles by means of image processing, and the velocity distribution can be measured.

The technique has been successfully applied to low velocity flows and is now being developed for flow velocities up to 100 m/sec.

The major features of this system are enumerated in the figure. I would like to emphasize that the data processing is quite rapid and requires only a PC-type computer.

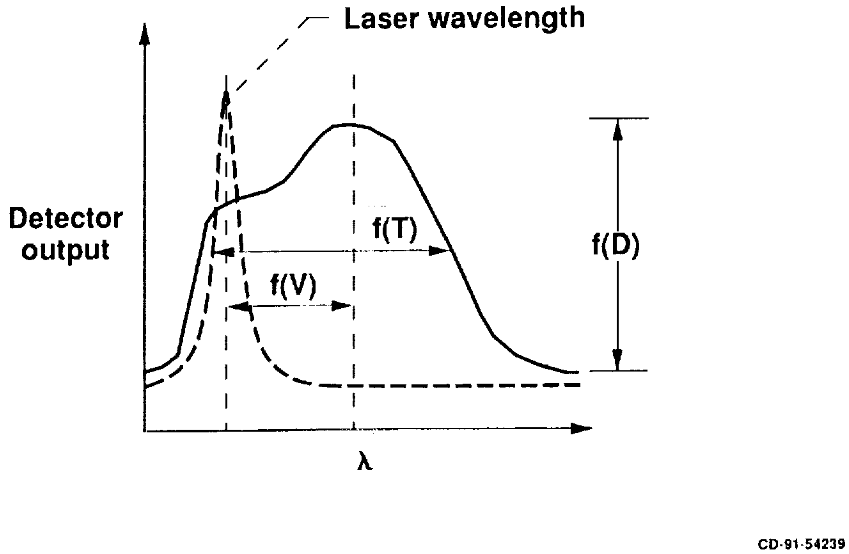


CD-91-54238

This is a photo of our newly developed Raleigh scattering system, which is used here to measure several parameters of the exhaust plume from a small hydrogen-oxygen rocket. A laser beam is focused at the point where the measurement is desired. The Rayleigh scattered photons are then collected and analyzed.

Rayleigh Scattering Diagnostics

Typical multiparameter data of plume velocity, V (4180 m/sec ± 4%), temperature, T (1110 K ± 3%), and density, D

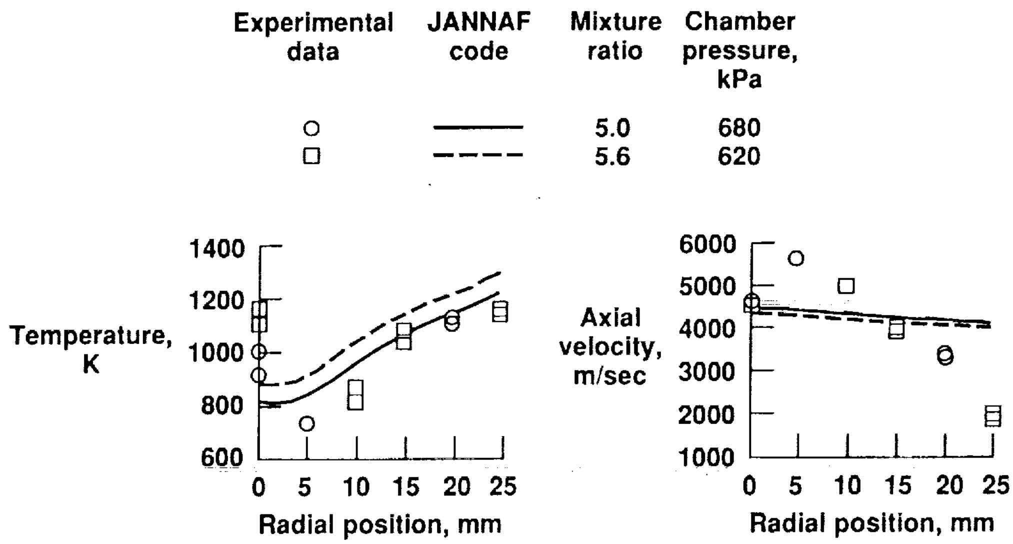


The interpretation of Rayleigh scattered light is dependent on the density regime.

For this rocket exhaust plume application, the parameters measured are (1) temperature, as determined from the line width of the received spectrum, (2) velocity, as determined by the displacement of the returned line from that of the incident laser, and (3) density, as determined by the amplitude of the returned line. This interpretation is valid only for situations of low density.

This technique is also being applied to temperature measurements in a 7-MN/m^2 hydrogen furnace. However, this high-density regime requires significantly different data interpretation.

Rayleigh Spectroscopy of Small H-O Rocket Plume



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As stated previously, the goal of many of these measurement systems is the validation of computer codes. The plume data shown here were the first of their kind obtained. These data revealed that the code predictions were accurate in predicting the average values of temperature and velocity, but inadequate in describing the radial variations of these parameters.

What Will the Use of These Thin-Film Sensors and Optical Systems Require of You?

- Investment in facilities, people, or closely coordinated contract, because the thin-film sensors must be fabricated on your specific hardware (not like buying a probe)
- Investment in highly skilled personnel to properly use the optical systems and to interpret the complex data that result from them

"Owning a Stradivarius doesn't make one a violinist"

CD-91-54241

This report has dealt with a variety of contact sensors, primarily thin film, and a variety of remote optical measuring systems. Their development has allowed us to make measurements which previously could not have been made; however, they come at a price.

The thin-film sensors must be fabricated with fairly sophisticated equipment, such as sputtering systems, on the very part on which the measurement is needed. In addition, application to each new material requires some sensor redevelopment. As a result a significant investment in both equipment and skilled personnel is required to achieve these sensors.

Similarly, the remote optical systems are frequently quite complex, both optically and in the data reduction area. Packaged systems can sometimes be purchased, but they cannot be used effectively by any but highly skilled personnel.

"Owning a Stradivarius doesn't make one a violinist."